Implications of a Light Higgs in Composite Models

Alex Pomarol, UAB (Barcelona)
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LHC Higgs searches have presented hints for a 125 GeV Higgs...

... and more to come very soon!
Purpose of my talk here:

**What are the implications of a 125 GeV Higgs in models in which the Higgs is a Composite Pseudo-Goldstone?**
Composite PGB Higgs

inspired by QCD where one observes that the (pseudo) scalar are the lightest states

Spectrum:

- GeV $\rho$
- 100 MeV $\pi$

Are Pseudo-Goldstone bosons (PGB)

Mass protected by the global QCD symmetry!

$\pi \rightarrow \pi + \alpha$
Can the light Higgs be a kind of a pion from a new strong sector?

We’d like the spectrum of the new strong sector to be:

\[ \text{Pseudo-Goldstone bosons (PGB)} \]

Minimal model: Spontaneous breaking in the strong sector:

\[ \text{SO}(5) \rightarrow \text{SO}(4) \]

4 Goldstones

Higgs doublet
Light Higgs since its mass comes from explicit breaking of the global symmetry due to the SM couplings:

\[ V(h) = \frac{g_{SM}^2 m_{\rho}^2}{16\pi^2} h^2 + \cdots \]

Difficult to get predictions due to the intractable strong dynamics!
AdS/CFT approach

Strongly-coupled systems in the Large $N_c$
Large $\lambda \equiv g^2 N_c$

Weakly-coupled Gravitational systems in higher-dimensions

Very **useful** to derive properties of **composite states** from studying weakly-coupled fields in warped extra-dimensional models
Holographic composite PGB Higgs model

**AdS\(_5\)** throat

\[ ds^2 = \frac{L^2}{z^2} \left[ dx^2 + dz^2 \right] \]

Holo. coordinate \( z \sim 1/E \)

hard/soft wall

Mass gap \( \sim \text{TeV} \)

Agashe, Contino, A.P.
Holographic composite PGB Higgs model

SO(5) gauge theory in a AdS$_5$ throat

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SO(5) gauge theory in a $\text{AdS}_5$ throat

$\frac{ds^2}{z^2} = \frac{L^2}{z^2} [dx^2 + dz^2]$

Holo. coordinate $z \sim 1/E$

Mass gap $\sim$ TeV

Symmetry: \textbf{SO}(4)

Breaking of symmetry by boundary conditions

Agashe, Contino, A.P.
Higgs = 5th component of the SO(5)/SO(4) gauge bosons
(Gauge-Higgs unification, Hosotani Mechanism, ...)

→ Normalizable modes = Composite
Simple geometric approach to fermion masses

\[ \psi(z) \]

1st & 2nd family
(Elementary)

3rd family
(\textbf{Top} = Most Composite)

hard/soft wall
$m_{\rho} = 2.5$ TeV , $f = 500$ GeV
For a 125 GeV Higgs, the fermionic resonances of the top are light \( \sim 600 \text{ GeV} \)
Simpler derivation of the connection: 

**Light Higgs - Light Resonance**

- Deconstruction: Matsedonskyi, Panico, Wulzer; Redi, Tesi 12
- Weinberg Sum Rules: Marzocca, Serone, Shu; AP, Riva 12

As Das, Guralnik, Mathur, Low, Young 67

for the charged pion mass:

\[ m_{\pi^+}^2 - m_{\pi^0}^2 \approx \frac{3\alpha}{2\pi} m_{\rho}^2 \log 2 \approx (37 \text{ MeV})^2 \]

Exp. (35 MeV)^2  

quite successful!
Higgs potential

Gauge contribution (limit $g'=0$):

$$V(h) = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \log \Pi_W$$

$$\Pi_W \simeq \frac{p^2}{g^2} + \frac{\sin^2 h/f}{2} \left[ \langle J_\hat{a} J_\hat{a} \rangle - \langle J_a J_a \rangle \right]$$

Encode the strong sector contribution to the gauge propagator in the $h$-background.
Easy derivation using **spurion techniques**:

\[
\mathcal{L} = \mathcal{L}_{\text{strong}} + \mathcal{L}_{\text{SM}} + J_{\text{strong}}^\mu W_\mu
\]

The most general SO(5) invariant action as a function of \( A_\mu \) after integrating out the strong sector:

\[
\mathcal{L}_{\text{eff}} = \frac{1}{2} P_{\mu\nu} \left[ \Pi_0(p) \text{Tr} [A_\mu A_\nu] + \Pi_1(p) \sum A_\mu A_\nu \Sigma^T \right] + \mathcal{O}(A^3)
\]

parametrizes the coset \( \text{SO}(5)/\text{SO}(4) \) (equivalents \( \text{SO}(4) \) vacuum)

\[\Sigma = \Sigma_0 e^{\Pi/f_\pi}, \quad \Sigma_0 = (0, 0, 0, 0, 1)\]
\[ \mathcal{L}_{\text{eff}} = \frac{1}{2} P_{\mu\nu} \left[ \Pi_0(p) \text{Tr}[A^\mu A^\nu] + \Pi_1(p) \Sigma A^\mu A^\nu \Sigma^T \right] + \mathcal{O}(A^3) \]

\[ A^\mu = W^\mu \]

\[ \langle \Sigma \rangle = (0, 0, 0, \sin h/f, \cos h/f) \]

\[ \langle \Sigma \rangle = (0, 0, 0, 0, 1) \]

\[ \Pi_W = \Pi_0 + \frac{\Pi_1}{4} \sin^2 \frac{h}{f}, \quad \Pi_a = \langle J_a J_a \rangle = \Pi_0 \]

\[ \Pi_{\hat{a}} = \langle J_{\hat{a}} J_{\hat{a}} \rangle = \Pi_0 + \frac{1}{2} \Pi_1 \]

\[ \Pi_0 \simeq \frac{p^2}{g^2} \]

\[ \Pi_W \simeq \frac{p^2}{g^2} + \frac{\sin^2 h/f}{2} \left[ \langle J_{\hat{a}} J_{\hat{a}} \rangle - \langle J_a J_a \rangle \right] \]

\[ A^\mu = W^\mu \]

\[ \langle \Sigma \rangle = (0, 0, 0, \sin h/f, \cos h/f) \]

\[ \langle \Sigma \rangle = (0, 0, 0, 0, 1) \]
**Higgs Mass from Weinberg Sum Rules**

**Gauge contribution:**

\[ V(h) = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \log \Pi_W = \frac{1}{2} m_h^2 h^2 + \cdots \]

\[ \Pi_1 = 2 [\langle J_\hat{a} J_{\hat{a}} \rangle - \langle J_a J_a \rangle] = f^2 + 2p^2 \sum_{n} \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_{n} \frac{F_{\rho_n}^2}{p^2 + m_{\rho_n}^2} \]

**Large N**

\[ = \sum_n \]
Higgs Mass from Weinberg Sum Rules

Gauge contribution:

\[ V(h) = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \log \Pi_W = \frac{1}{2} m_h^2 h^2 + \cdots \]

\[ \Rightarrow m_h^2 \approx \frac{9g^2}{2f^2} \int \frac{d^4p}{(2\pi)^4} \frac{\Pi_1(p)}{p^2} \]

\[ \Pi_1 = 2 [\langle J_\hat{a} J_\hat{a} \rangle - \langle J_a J_a \rangle] = f^2 + 2p^2 \sum_n^{\infty} \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_n^{\infty} \frac{F_{\rho_n}^2}{p^2 + m_{\rho_n}^2} \]

Procedure:

1) Demand convergence of the integral:

\[ \lim_{p^2 \to \infty} \Pi_1(p) = 0 , \quad \lim_{p^2 \to \infty} p^2 \Pi_1(p) = 0 . \quad \text{“Weinberg Sum Rules”} \]
Higgs Mass from Weinberg Sum Rules

Gauge contribution:

\[ V(h) = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \log \Pi_W = \frac{1}{2} m_h^2 h^2 + \cdots \]

\[ \Pi_1 = 2 \left[ \langle J_\alpha J_\alpha \rangle - \langle J_a J_a \rangle \right] = f^2 + 2p^2 \sum_{n} \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_{n} \frac{F_{\rho_n}^2}{p^2 + m_{\rho_n}^2} \]

Procedure:

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\[ \left[ \langle J_\alpha J_\alpha \rangle - \langle J_a J_a \rangle \right] \sim \frac{\langle \mathcal{O} \rangle}{p^{d-2}} + \cdots \]

Just from the OPE at large \( p \)

\( d = \text{Dim}[\mathcal{O}] \quad \Rightarrow \text{symmetry breaking operator} \)

\( \Rightarrow \text{WSR = demand } d > 4 \)
Higgs Mass from Weinberg Sum Rules

Gauge contribution:

\[ V(h) = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \log \Pi_W = \frac{1}{2} m_h^2 h^2 + \cdots \]

\[ \Pi_1 = 2 [\langle J_\alpha J_\alpha \rangle - \langle J_a J_a \rangle] = f^2 + 2p^2 \sum_n \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_n \frac{F_{\rho_n}^2}{p^2 + m_{\rho_n}^2} \]

Procedure:

1) Demand convergence of the integral:

\[ \lim_{p^2 \to \infty} \Pi_1(p) = 0 \,, \quad \lim_{p^2 \to \infty} p^2 \Pi_1(p) = 0 \, \text{“Weinberg Sum Rules”} \]

E.g. in QCD:

\[ \Pi_{LR}(p) = \Pi_V - \Pi_A \to \langle q\bar{q} \rangle^2 / p^4 \]
Higgs Mass from Weinberg Sum Rules

Gauge contribution:

\[ V(h) = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \log \Pi_W = \frac{1}{2} m_h^2 h^2 + \cdots \]

\[ \Pi_1 = 2 [\langle J_\hat{a} J_\hat{a} \rangle - \langle J_a J_a \rangle] = f^2 + 2p^2 \sum_n^{\infty} \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_n^{\infty} \frac{F_{\rho_n}^2}{p^2 + m_{\rho_n}^2} \]

Procedure:

1) Demand convergence of the integral:

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\lim_{p^2 \to \infty} \Pi_1(p) = 0 , \quad \lim_{p^2 \to \infty} p^2 \Pi_1(p) = 0 . \quad \text{“Weinberg Sum Rules”}
\]

2) Correlators dominated by the lowest resonances

(minimal number to satisfy WSR)
Result: two resonances needed: \( \rho \) and \( a_1 \)

\[
\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)}
\]

\[
m_h^2 \simeq \frac{9g^2 m_\rho^2 m_{a_1}^2}{64\pi^2 (m_{a_1}^2 - m_\rho^2)} \log \left( \frac{m_{a_1}^2}{m_\rho^2} \right)
\]

Similar result as the electromagnetic contribution to the charged pion mass
Similarly, for the top contribution...

\[ \mathcal{L} = \mathcal{L}_{\text{strong}} + \mathcal{L}_{\text{SM}} + J_{\text{strong}}^\mu W_\mu + \mathcal{O}_{\text{strong}} \cdot \psi_{\text{SM}} \]

we must specify which rep of SO(5)

\[ \text{MCHM}_5 \equiv \text{Rep}[\mathcal{O}] = 5 \]

Top contribution to the Higgs potential:

\[ V(h) = -2N_c \int \frac{d^4p}{(2\pi)^4} \log \left[ -p^2 (\Pi^{tL} \Pi^{tR}) - |\Pi^{tLtR}|^2 \right] \]

Encode the strong sector contribution to the top propagator in the h-background
\[ V(h) = -2N_c \int \frac{d^4p}{(2\pi)^4} \log \left[ -p^2 \left( \Pi_{tL} \Pi_{tR} \right) - |\Pi_{tL tR}|^2 \right] \]

\[ = -m^2 h^2 + \lambda_h h^4 + \cdots \]

Triggers EWSB!
Higgs mass contribution:

\[ m_h^2 \sim \frac{8N_c v^2}{f^4} \int \frac{d^4p}{(2\pi)^4} \left[ \|M_1^t\|^2 + \frac{1}{4} (\Pi_{1L}^{tL})^2 + (\Pi_{1R}^{tL})^2 \right] \]

\[
\begin{align*}
\Pi_{1L}^{tL}(p) &= \Pi_{Q_1}^L(p) - \Pi_{Q_4}^L(p), \\
\Pi_{1R}^{tR}(p) &= \Pi_{Q_1}^R(p) - \Pi_{Q_4}^R(p), \\
M_1^t(p) &= M_{Q_1}(p) - M_{Q_4}(p).
\end{align*}
\]

Large N: \[ \Pi_{Q_4}^L(p) = \sum_n \frac{|F_{Q_4}^{L(n)}|^2}{p^2 + m_{Q_4}^{(n)}} , \quad \Pi_{Q_1}^L(p) = \sum_n \frac{|F_{Q_1}^{L(n)}|^2}{p^2 + m_{Q_1}^{(n)}} , \]

and similarly for \( \Pi_{Q_4,1}^R \) with the replacement \( L \rightarrow R \), while

\[ M_{Q_4}(p) = \sum_n \frac{F_{Q_4}^{L(n)} F_{Q_4}^{R(n)\ast} m_{Q_4}^{(n)}}{p^2 + m_{Q_4}^{(n)}} , \quad M_{Q_1}(p) = \sum_n \frac{F_{Q_1}^{L(n)} F_{Q_1}^{R(n)\ast} m_{Q_1}^{(n)}}{p^2 + m_{Q_1}^{(n)}} . \]
Demanding again WSR:

\[
\lim_{p \to \infty} M_1^t(p) = 0
\]

\[
\lim_{p \to \infty} p^n \Pi_1^{tL,R}(p) = 0 \ (n = 0, 2)
\]

... being fulfilled with the minimal set of resonances, two in this case, \(Q_1\) and \(Q_4\):

\[
\Pi_1^{tL,R} = |F_{Q_4}^{L,R}|^2 \frac{(m_{Q_4}^2 - m_{Q_1}^2)}{(p^2 + m_{Q_4}^2)(p^2 + m_{Q_1}^2)}
\]

\[
M_1^t(p) = |F_{Q_4}^L F_{Q_4}^{R*}| \frac{m_{Q_4} m_{Q_1} (m_{Q_4} - m_{Q_1} e^{i\theta})}{(p^2 + m_{Q_4}^2)(p^2 + m_{Q_1}^2)} \left(1 + \frac{p^2}{m_{Q_4} m_{Q_1} m_{Q_4} - m_{Q_1} e^{i\theta}}\right)
\]
WSR + Minimal set of resonances ($Q_1$ and $Q_4$) + proper EWSB

\[ m_h^2 \sim \frac{N_c}{\pi^2} \left[ \frac{m_t^2}{f^2} \frac{m_{Q_4}^2}{m_{Q_4}^2 - m_{Q_4}^2} \log \left( \frac{m_{Q_1}^2}{m_{Q_4}^2} \right) \right] \]

For a 125 GeV Higgs:
\[ m_h^2 \simeq \frac{N_c}{\pi^2} \left[ \frac{m_t^2}{f^2} \frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2} \log \left( \frac{m_{Q_1}^2}{m_{Q_4}^2} \right) \right] \]

For a 125 GeV Higgs:

Also for other representations:

\[ \text{MCHM}_{10} \equiv \text{Rep}[\mathcal{O}] = 10 \]
At the LHC...

If a 125 GeV Higgs is confirmed...
At the LHC...

If a 125 GeV Higgs is confirmed...

look for color vector-like fermions in the $4$ or $1$ of SO(4):

EM charges: $5/3, 2/3, -1/3$
Color vector-like fermions with charge 5/3:

If this fermion is light, it can be double produced:

same-sign di-leptons

Contino, Servant
Mrazek, Wulzer
Aguilar-Saavedra, Dissertori, Furlan, Moorgat, Nef
But also deviations from SM Higgs couplings expected:

\[ \bar{f}_L f_R \sin^{1+m} \frac{h}{f} \cos^n \frac{h}{f} \quad (m, n = 0, 1, 2, \ldots) \]

depending on the embedding of the fermions (n=0,1,...) and v/f
Conclusions

Probably **Nature** has chosen a light Higgs for EWSB (>99% CL)

- Composite Higgs as a PGB a natural possibility (Higgs mass at the loop level)
- A 125 GeV composite Higgs implies either from AdS/CFT, Weinberg Sum rules, deconstructed models:
  
  **Fermionic colored vector-like resonances** (either $Q^{em} = 5/3, 2/3, -1/3$) with masses
  
  $\sim 500-700$ GeV

  **Hope to see them at the LHC !**